Physics-Based High Performance Computing Using Higher-Order Methods for Broadband Applications in Computational Electromagnetics (CEM)

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ABSTRACT

Under sponsorship from various Department of Defense (DoD) organizations and a Cooperative Research and Development Agreement (CRADA) with the U.S. Research, Development and Engineering Command, Army Research Laboratory (RDECOM-ARL), HyPerComp has significantly advanced the state of the art of time-domain, broad band electromagnetic simulations. The **TEMPUS** (**T**ime-Domain **E**lectro**M**agnetic **P**arallel **U**nstructured **S**imulator) environment is a complete self contained code suite that includes computer aided design (CAD) geometry creation and repair, unstructured gridding for full-scale targets with general materials, scalable parallel code architecture, higher-order accurate discontinuous Galerkin solvers for Maxwell's equations, and post processing utilities for solution visualization and extraction of final results like bistatic and monostatic radar cross section (RCS), synthetic aperture radar (SAR) images, and high-range-resolution (HRR) profiles. The high-performance TEMPUS environment is well suited for modeling a variety of targets and electromagnetic problems of interest to the U.S. Army such as: 1) high-speed projectiles with subtle surface discontinuities, ridges and/or fins, 2) ground-based targets such as tanks and scud missile launchers, and 3) foliage penetration and ground interaction for target under trees (TUT). Some of the physics-based phenomenological features that govern the electromagnetic response of general targets are: a) specular reflection, b) creeping waves, c) traveling waves, d) slow moving surface waves, e) edge diffraction, f) singular currents at surface discontinuities, g) resonating gaps and cavities, and h) general material response.

1. INTRODUCTION

The ability to accurately predict the scattering and radiation behavior for broadband (up to 100 GHz) electromagnetic illumination over complex targets with geometrical details including surface discontinuities, gaps, cracks, thin edges, cavities and embedded antennae coupled with material treatments is a critical technology need for DoD. There are three basic approaches to numerical simulation of Maxwell's equations: 1) high frequency asymptotics, which treats scattering and diffraction as local phenomena, 2) solution of an integral equation (frequency domain) for radiating sources on (or inside) the scattering body, which couples all parts of the body through a multiple scattering process, and 3) the direct integration of the differential form of Maxwell's equations in time. Accurate prediction for broadband electromagnetic illumination is currently too computationally expensive to be effectively addressed by multiple applications of even the fastest frequency domain techniques. The integration of Maxwell's equations in time offers the most direct and general solution for broadband radar scattering and propagation of electromagnetic pulses in real materials. Time-domain methods may be the best approach for applications such as SAR imagery that require large bandwidths and hundreds of aspect angles. The challenge for time-domain methods has been to maintain global accuracy in the phase and amplitude of waves scattered by large, complex structures. This requires a well-conditioned time/space discretization procedure that exhibits high-order convergence, fast and scalable computation with memory efficiency, and numerical fidelity through mathematical error control.

Many of the earlier time-domain integration methods suffered serious limitations in the accuracy with which boundary conditions could be satisfied, both on the target and at the outer limits of the computational domain, leading to significant numerical discretization errors (Warming and Beam, 1976; Rowell et al. 1995). Von Neumann analysis on regular grids shows the limitations of low-order integration schemes in propagating waves over distances long compared to a wavelength. The standard second-order upwind approach suffers large dispersion and damping effects when it is applied directly to cell averages of the fields in a second-order time integration scheme, such as the one devised by Warming and Beam. This is true even though the scheme maintains second-order accuracy in space as well. The impact of these errors on RCS computational accuracy can be significant, especially when waves scattered strongly

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from different parts of the target come together with comparable amplitudes elsewhere on the target surface, or combine in the far field with large relative errors in phase.

We have undertaken the development of a state-of-the-art time-domain computational electromagnetics (CEM) technology known as **TEMPUS** (**T**ime-Domain **EM P**arallel **U**nstructured **S**imulator). TEMPUS includes all aspects of a CEM simulation including CAD geometry modeling and repair, unstructured gridding for full-scale targets with general materials, parallel run set up (for PC- and workstation clusters) and higher-order accurate solvers for Maxwell's equations, and post processing utilities for solution visualization and extraction of final results like bistatic and monostatic RCS, SAR images, and HRR profiles.

The numerical method at the heart of TEMPUS integrates the full set of Maxwell's equations in general media, optimized for the evaluation of radar signatures for arbitrary targets that may be up to a few hundred wavelengths across in the largest dimension. The method is an implementation of the discontinuous Galerkin approach developed by Cockburn and Shu in 1998 for solving hyperbolic equations in the time domain on unstructured grids. A description of this implementation may be found in the recent paper by Kabakian et al.. (2004) Some of the notable qualities of this higher-order approach include extremely low phase errors, the ability to preserve accuracy in the presence of highly irregular unstructured meshes, straightforward interfacing with material boundaries, and straightforward parallelization.

The objective of this paper is to highlight the capabilities of TEMPUS in simulating various electromagnetic features and to illustrate the accuracy of TEMPUS results using comparisons to measured data.

1.1 Physics of Maxwell's equations

The integration of Maxwell's equations in time offers the most direct and general solution for broadband radar scattering and propagation of electromagnetic pulses in real materials. The challenge for time-domain methods has been to maintain global accuracy in the phase and amplitude of waves scattered by large, complex structures. In addition, some of these methods have suffered serious limitations in the accuracy with which boundary conditions could be satisfied both on the target and at the outer limits of the computational domain.

The sources of the electromagnetic fields of interest are typically currents on antenna structures and polarizations induced in target materials by incident radar pulses. The simplest case of plane-wave reflection by a metal aircraft can be treated as a problem in determining the currents induced on the aircraft surface. Other cases of interest, such as the interaction of high-power microwave pulses with shielding of various kinds, require tracking the buildup of field amplitudes inside the materials, which can trigger electrical breakdown or even changes in physical state. Such processes depend nonlinearly on the local field strength, and consequently they are not amenable to the frequency-domain description traditionally employed in radar scattering, which assumes that the target response is linear in the local fields.

1.2 High-Order Discontinuous Galerkin Solver

Scattering from many targets of interest to the DoD is dominated by surface traveling waves and cavities, which require modeling long distance wave propagation with high accuracy. This very challenging requirement for numerical schemes is currently met by employing very fine meshes, which can quickly exhaust computational resources. Numerous numerical experiments have shown, however, that high-order methods are far more efficient for solving scattering problems that require this high accuracy. Indeed, although high-order methods are more computationally expensive per grid cell than low-order methods, they require fewer cells to approximate the solution with the same accuracy.

Also, singularities in the exact solution can cause errors to accumulate globally in the numerical solution for some approaches. Even for more robust schemes, resolving the surface currents in the vicinity of a physical discontinuity (edge, corner, and tip) may be required to predict the strength of the diffracted fields with acceptable accuracy.

Using the discontinuous Galerkin method, HyPerComp has successfully developed the unstructured, parallel, high-order solver TEMPUS, representing a significant leap in the state of the art in time-domain CEM. The discontinuous Galerkin method has three key properties that we have found to be essential for performing fast and accurate simulations for electrically large and complex targets:

1. *Unstructured hybrid grid* support to handle complex realistic target geometries.
2. *Highly scalable parallelization* to exploit massively parallel computers.
3. *High-order discretization* to model accurately long distance propagation and complex wave interactions.

A brief description of the discontinuous Galerkin method is given by Kabakian et al. (2004)

2. TEMPUS VALIDATIONS

To assess the wave propagation properties of the discontinuous Galerkin method, a number of numerical experiments have been performed in one- and two-dimensions. Using the one-dimensional wave equation, a Gaussian pulse, having 9 cells across its width at half-maximum, is propagated over 5000 cell-widths with the Galerkin method using polynomials of degrees zero, one, and two. The results for a standard second-order accurate "RK4" algorithm (Rowell et al.,1995) and the Galerkin schemes (Kabakian et al. 2004) are shown in Figure 1.

RK4　　　　**Galerkin-p0**

Galerkin-p1　　　　**Galerkin-p2**

Fig. 1. One dimensional wave propagation.

The "RK4" algorithm has distorted the shape of the pulse, which is indicative of the large accumulation of phase errors. In contrast, the Galerkin-p0 solution exhibits high levels of dissipation. Both methods require much finer meshes to preserve accuracy over such a long propagation distance. But the Galekin-p1, and especially the Galerkin-p2, solutions have retained the pulse shape remarkably well. Furthermore, in contrast to the "RK4" scheme, the dominant type of error for DG is dissipation, with phase error always remaining very low. This makes the Galerkin schemes extremely attractive for accurately simulating the constructive and deconstructive interferences that occur in problems dominated by traveling waves and multiple-bounces.

2.1 Creeping Wave Prediction

While the case of a sphere is geometrically simple, the TEMPUS broad band capability accurately predicts the creeping wave behavior that shows up as a late time return in the HRR profile. This is illustrated for a sphere in Figure 2. The broadband RCS results and the associated HRR profile for a sphere (radius of 40" or 1 meter) for frequencies from 0 to 2 GHz are shown. The

RCS variation as a function of frequency is compared with the Mie series solution. The HRR profile clearly shows the presence of a creeping wave. After the first range signal that corresponds to the pulse striking the nose of the sphere, a creeping wave signal shows a response at a range given by the diameter+ *radius. In the HRR profile this corresponds to a response located approximately 62.8" from the center of the sphere.
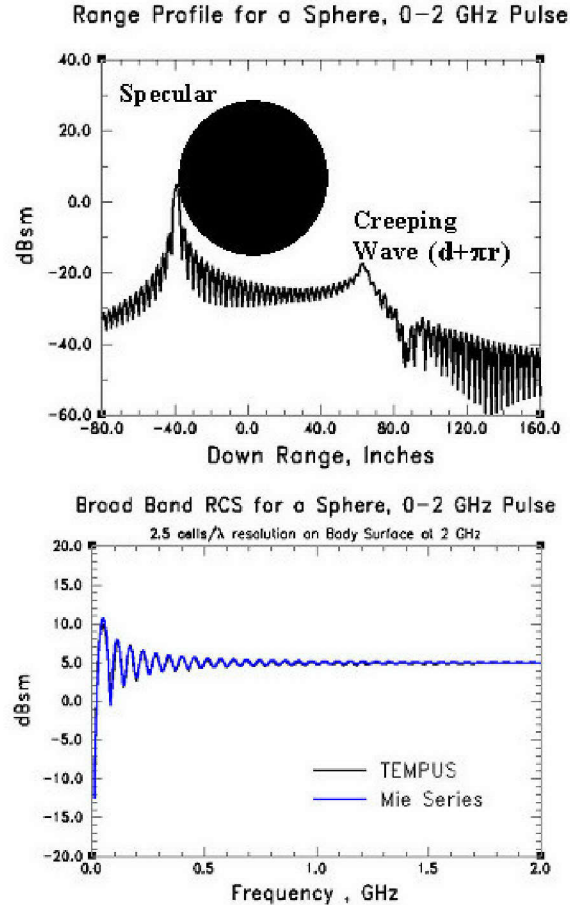

Fig. 2. Specular and creeping waves for a sphere.

2.2 Traveling Wave RCS

Usually, any long and thin object will trigger a traveling wave pattern that dominates the backscatter return at certain grazing incidence angles. Accurate prediction of traveling wave RCS is a challenge for numerical methods. The high-order formulation inherent in the TEMPUS solver is well suited for computing such traveling wave behavior. Many examples are shown here to illustrate the traveling wave RCS prediction by TEMPUS. Figure 3 shows RCS results for a business card size flat plate target that is dominated by the presence of a traveling wave at grazing angles. Figures 4 and 5 show results for a long and slender 10" ogive that exhibit a strong traveling wave for near nose-on incidence. The backscatter RCS and the 90^0 bistatic RCS predicted by TEMPUS compare quite well with data

measured by the National Radar Test Facility. Figure 5 shows a large backscatter RCS due to a traveling wave that occurs at an incident azimuth angle of 8^0 which is not present at an incident angle of 0^0.
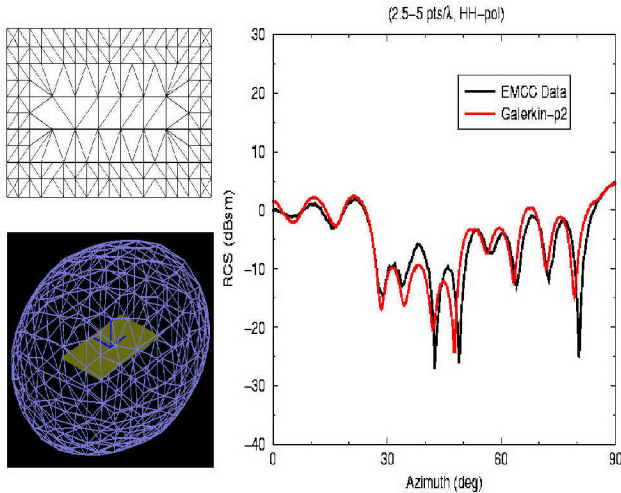

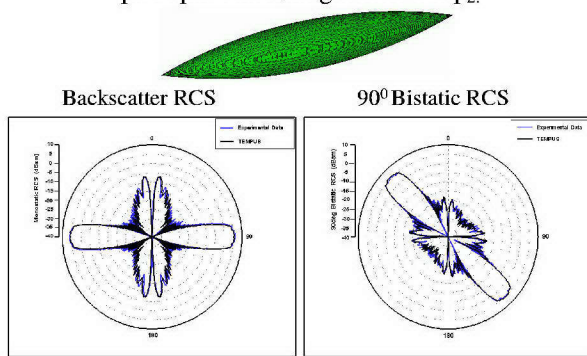Fig. 3. Monostatic RCS for 3.5 by 2 business-card flat-plate problem using TEMPUS-p_2.

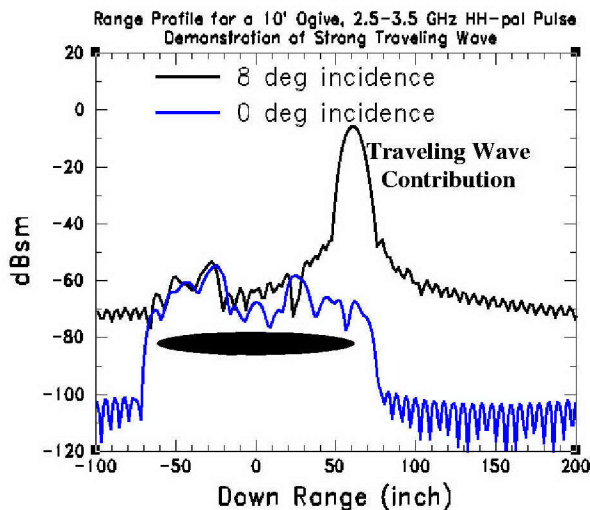Fig. 4. TEMPUS accurately predicts the traveling wave for a 10" ogive.

Fig. 5. Range profile showing a strong traveling wave return for an incidence angle of 8^0 from nose-on.

Figure 6 shows the range profile for a 50-caliber bullet at near nose-on incidence. The measurements were made at frequencies between 32.4-35.6 GHz. This results in a down-range resolution of 1.85". The measured range profile and the TEMPUS simulation for the same bandwidth compare well. A simulation was also performed using 20-GHz of bandwidth and a range resolution of 0.3". The range profile shows two peaks, one corresponding to the tip and one corresponding to the back end of the bullet.
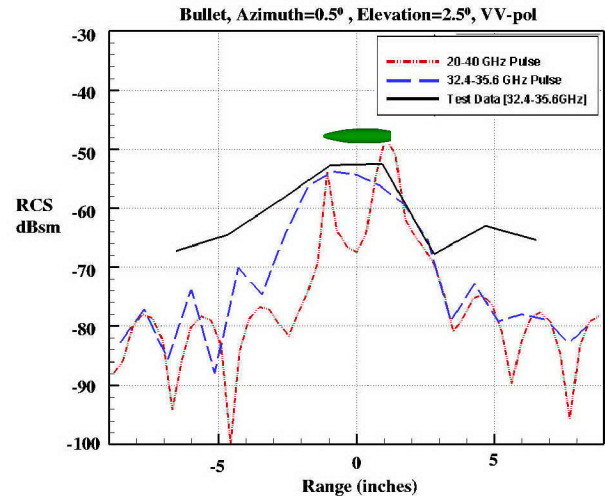

Fig. 6. Range profile for a bullet at near nose-on incidence angle.

2.3 Small Geometrical Features on Large Targets

One of the challenges of CEM is to be able to model small geometrical features on a large target (Walter 1965). These include gaps, cracks, sharp edges, and thin wires. While it may be possible to model these small regions through appropriate basis functions that represent the singular behavior of EM fields in their vicinity, we are exploiting the TEMPUS high-order capability by gridding the large and small geometrical features through appropriate grid resolutions leading to very small grid cells being present along with large cells.

The class of missile-like objects is of interest to the Army. Small variations in surface continuity on a cone-cylinder body can cause dramatic changes in backscatter RCS. Three simple missile-like geometries, shown in Figure 6, were tested to study the effect of such variations, The tip-a geometry has a 90^0 step on the cylinder body where tip-b has a step with a rounded edge.. Tip-c has a step on the front cone in addition to the rounded edge step of tip-b. Results were generated for these geometries at a center frequency of 34 GHz (Ka band). Figure 7 shows a comparison of HRR profiles for tip-a and tip-b, and a similar one shown in Figure 8 for tip-b and tip-c. The HRR profile clearly shows a large drop in backscatter return from the rounded edge relative

to the sharp edge . Figure 9 shows a comparison of the backscatter RCS for tip-a with measured data (Pizzillo and Wellman, 2003). The comparison is quite good despite the fact that the CAD file geometry was not an exact representation of the measured target. The high frequency code, Xpatch, did not predict the behavior of such subtle surface discontinuities for head-on aspect angles (C. Kenyon 2004, personal communication).
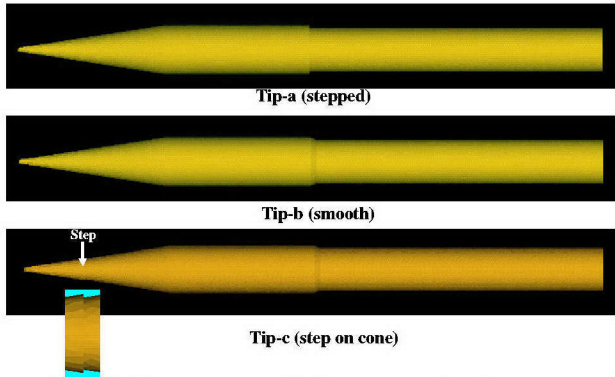

Fig. 6. Three cone-cylinder geometries that were measured and simulated.
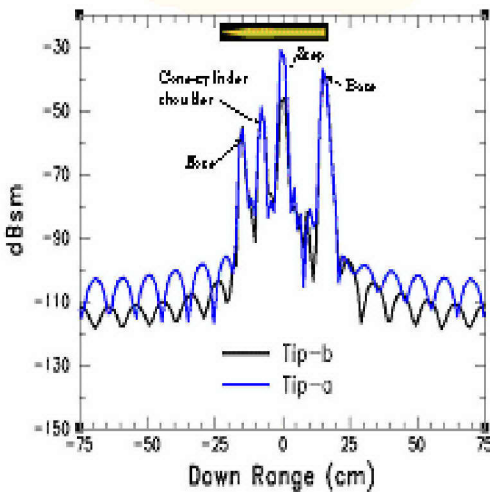

Fig. 7. Range profile for a 14-GHz bandwidth (24- 40 GHz) clearly shows the return from regions of surface discontinuity.

2.4 Slow Moving Surface Waves

Missile-like targets exhibiting a certain pattern of surface grooves can encounter slow moving surface waves. TEMPUS can demonstrate the presence of such slow moving surface waves for a simple corrugated cylinder. Depending on the corrugation geometry (depth and width of corrugation and number of corrugations per wavelength), the degree of slowness of surface waves is altered. Figure 10 shows the geometry and gridding for a corrugated cylinder along with a simulated range profile

for a 32-36 GHz pulse. This result shows a return peak well past the end of the corrugation shown in yellow indicating the presence of a slow moving surface wave. Figure 11 shows a comparison of range profiles for a cylinder with and without corrugations of a certain size. When the corrugation is removed, the range profile shows no sign of a slow moving wave. This phenomenology has been confirmed with measurement results provided under the CRADA. Such features dominate the RCS of many realistic slender targets but are often overlooked in less accurate simulations.
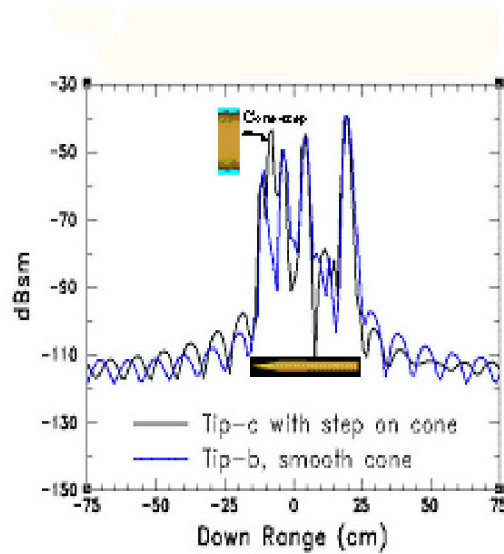

Fig. 8 Range profile for a 14-GHz bandwidth (24- 40 GHz) with a surface discontinuity on the cone tip.
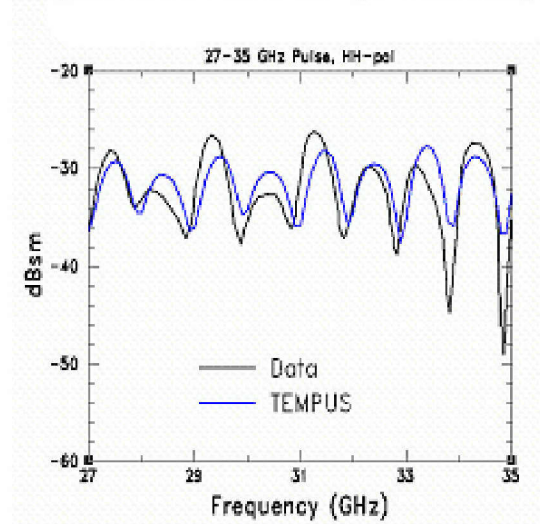

Fig. 9. Comparison of RCS vs frequency between measured data and TEMPUS for Tip-a.
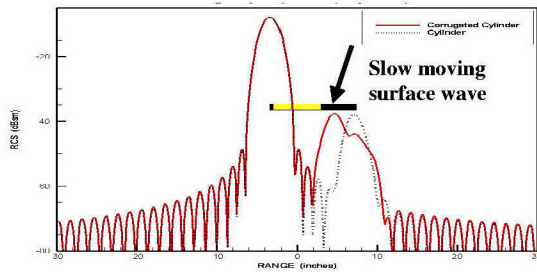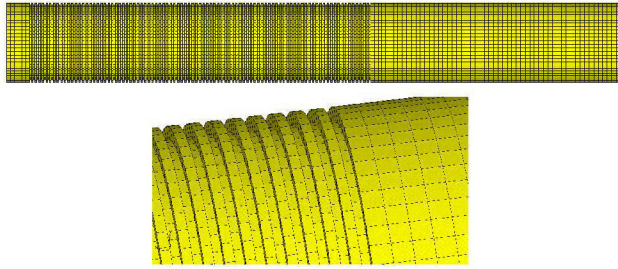
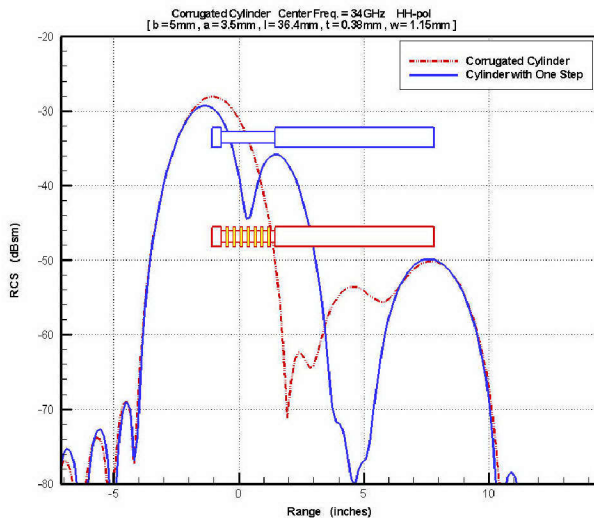Fig. 10. TEMPUS simulation of slow moving surface wave on a corrugated cylinder.

Fig. 11. Effect of corrugation on slow moving surface wave.

2.5 Fine Grain Parallel Environment

The TEMPUS environment is designed for a high level of efficiency to be able to effectively solve large-scale simulations on fine grain parallel clusters. More recently, the major emphasis is on developing the entire TEMPUS simulation process from start to finish on low cost Linux-based PC-clusters. HyPerComp is working on both the software related issues such as compiler options (Redhat LINUX versions from 5.0 through 9.0 or Solaris-86), operating system versions, porting graphical tools to different platforms, appropriate MPI libraries for message passing, version control and software security, as well as hardware issues such as network information service

(NIS), ethernet cables, switches, routers and hubs, rack mounts and power supply for fine-grain clusters. HyPerComp is currently installing a 128-node PC cluster using Pentium IV, 2.2-GHz motherboard with at least 1 Gb memory/node. We are also documenting the lessons learned in configuring and setting up both the hardware and software for PC clusters.

3. CONCLUSION

The radar cross section of many realistic targets is influenced by several physics-based electromagnetic phenomena such as creeping waves, traveling waves and slow moving surface waves that are difficult to simulate and require a very accurate prediction capability to reproduce. Employing higher-order algorithms, the time-domain environment TEMPUS has demonstrated these phenomena.

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